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## Inflation and cosmic (super)strings: implications of their intimate relation revisited

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# Inflation and cosmic (super)strings: implications of their intimate relation revisited

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**Abstract.** We briefly discuss constraints on supersymmetric hybrid inflation models and examine the consistency of brane inflation models. We then address the implications for inflationary scenarios resulting from the strong constraints on the cosmic (super)string tension imposed from the most recent cosmic microwave background temperature anisotropies data.

## 1. Introduction

Cosmological inflation Starobinsky (1980); Guth (1980); Linde (1981) offers, by construction, a simple way to evade some of the problems related to the initial conditions that plague the hot big bang model. In addition, inflation can provide a simple mechanism to get adiabatic perturbations that seem to lead to the observed large scale structure and the measured Cosmic Microwave Background (CMB) temperature anisotropies. However, despite efforts over more than three decades, inflation remains a paradigm in search of a model. Apart from the issues related to the onset of inflation Calzetta & Sakellariadou (1992, 1993); Germani *et al.* (2007), particle physics models indicate difficulties in order to satisfy the required properties of the scalar field that would play the rôle of the inflaton.

The main bulk of efforts to realise an inflationary scenario is concentrated on a scalar (single or multiple) field type of inflation. The simple minimal case of a Higgs field driven inflation Bezrukov & Shaposhnikov (2008) faces important difficulties Buck *et al.* (2010) and inconsistencies Barbon & Espinosa (2009); Atkins & Calmet (2011). In the context of supersymmetric Grand Unified Theories (GUTs), hybrid inflationary models end with the formation of cosmic strings Jeannerot *et al.* (2003), which to be compatible with the CMB measurements require fine tuning of the free parameters (couplings and mass scales) of the inflationary potential Rocher & Sakellariadou (2005a,b, 2006); Battye *et al.* (2010). Moreover, the singlets of the Standard Model (SM) seem to encounter difficulties in order to play the rôle of the inflaton, as it has been recently shown Cacciapaglia & Sakellariadou (2013) in the case of the minimal SO(10) model.

One can argue that inflation must be studied in the context of an Ultra-Violet (UV) complete theory and as such, string theory is a well-studied candidate. Within this framework, brane inflation models, which are the ones that have been more extensively studied, lead to the formation of cosmic superstrings whose observational consequences may offer a way of constraining the underlying string theory. However, Supergravity (SUGRA) constraints Komargodski & Seiberg (2009); Dienes & Thomas (2010); Komargodski & Seiberg (2010)



imply the existence of severe difficulties for the realisation of at least one class (of the two studied classes) of brane inflationary models Gwyn *et al.* (2011) proposed in the context of IIB string theory. Moreover, constraints are also imposed on the allowed radiation emitted from the produced cosmic superstrings Gwyn *et al.* (2011).

The difficulties in realising a scalar field based inflationary model, which on the one hand is consistent with particle physics and CMB measurements, while on the other hand it satisfies minimal naturalness criteria, may be overthrown if one changes the gravitational sector of the theory, adding for instance an  $R^2$ -term Starobinsky (1980); Gottlober *et al.* (1991), without changing its particle content. This approach avoids on the one hand the constraints imposed due to the generically formed cosmic (super)strings, which remain undetectable Ade *et al.* (2013), and on the other hand the (by hand) addition of an extra singlet to play the rôle of the inflaton. Note that it is certainly reasonable to expect corrections to the low-energy effective gravitational action, as for instance within noncommutative spectral geometry Kurkov & Sakellariadou (2014), moreover models with high curvature terms seem to be favoured by the recent Planck CMB measurements Ade *et al.* (2013).

In what follows, we will briefly review the constraints on supersymmetric hybrid inflation, the consistency of brane inflation models, as well as the constraints on the allowed radiation of cosmic superstrings. We will then highlight some open questions which deserve to be addressed given the precision of current astrophysical and particle physics measurements and the plethora of cosmological scenarios.

## 2. Supersymmetric hybrid inflation

Models based upon  $N = 1$  SUSY contain complex scalar fields which often have flat directions in their potential, offering candidates for inflationary models. Within this framework, hybrid inflation driven by F- or D-terms represents the standard inflationary model, which leads Jeannerot *et al.* (2003) generically to cosmic string formation at the end of the inflationary era.

F-term inflation can be naturally accommodated in the framework of GUTs when a GUT gauge group,  $G_{\text{GUT}}$ , is broken down to the SM gauge group,  $G_{\text{SM}}$ , at an energy scale  $M_{\text{GUT}}$  according to the scheme

$$G_{\text{GUT}} \xrightarrow{M_{\text{GUT}}} H_1 \xrightarrow[\Phi_+ \Phi_-]{M_{\text{infl}}} H_2 \longrightarrow G_{\text{SM}} , \quad (1)$$

where  $\Phi_+, \Phi_-$  is a pair of GUT Higgs superfields in non-trivial complex conjugate representations, which lower the rank of the group by one unit when acquiring non-zero vacuum expectation value. The inflationary phase takes place at the beginning of the symmetry breaking  $H_1 \xrightarrow{M_{\text{infl}}} H_2$ . The gauge symmetry is spontaneously broken by adding F-terms to the superpotential. The Higgs mechanism leads generically Jeannerot *et al.* (2003) to Abrikosov-Nielsen-Olesen strings, called F-term strings.

F-term inflation is based on the globally supersymmetric renormalisable superpotential

$$W_{\text{infl}}^{\text{F}} = \kappa S (\Phi_+ \Phi_- - M^2) , \quad (2)$$

where  $S$  is a GUT gauge singlet left handed superfield and  $\kappa, M$  are two constants ( $M$  has dimensions of mass) which can be taken positive with field redefinition. The scalar potential as a function of the scalar complex component of the respective chiral superfields  $\Phi_{\pm}, S$  reads

$$V(\phi_+, \phi_-, S) = |F_{\Phi_+}|^2 + |F_{\Phi_-}|^2 + |F_S|^2 + \frac{1}{2} \sum_a g_a^2 D_a^2 . \quad (3)$$

The F-term is such that  $F_{\Phi_i} \equiv |\partial W / \partial \Phi_i|_{\theta=0}$ , where we take the scalar component of the superfields once we differentiate with respect to  $\Phi_i = \Phi_{\pm}, S$ . The D-terms are  $D_a =$

$\bar{\phi}_i (T_a)^i_j \phi^j + \xi_a$ , with  $a$  the label of the gauge group generators  $T_a$ ,  $g_a$  the gauge coupling, and  $\xi_a$  the Fayet-Iliopoulos (FI) term. By definition, in the F-term inflation the real constant  $\xi_a$  is zero; it can only be non-zero if  $T_a$  generates an extra U(1) group. In the context of F-term hybrid inflation the F-terms give rise to the inflationary potential energy density while the D-terms are flat along the inflationary trajectory, thus one may neglect them during inflation.

D-term inflation has been studied a lot in the literature, in particular since it can be naturally implemented within SUSY GUTs, SUGRA, or string theories. The gauge symmetry is spontaneously broken by introducing FI D-terms. In standard D-term inflation, the constant FI term gets compensated by a single complex scalar field at the end of the inflationary era, leading to the formation of cosmic strings, called D-term strings.

Standard D-term inflation is realised within a scheme, such as

$$G_{\text{GUT}} \times U(1) \xrightarrow{M_{\text{GUT}}} H \times U(1) \xrightarrow[\Phi_+ \Phi_-]{M_{\text{infl}}} H \rightarrow G_{\text{SM}} . \quad (4)$$

It is based on the superpotential

$$W = \lambda S \Phi_+ \Phi_- , \quad (5)$$

where  $S, \Phi_+, \Phi_-$  are three chiral superfields and  $\lambda$  is the superpotential coupling. It assumes an invariance under an Abelian gauge group  $U(1)_\xi$ , under which the superfields  $S, \Phi_+, \Phi_-$  have charges 0, +1 and -1, respectively. It also assumes the existence of a constant FI term  $\xi$ .

Note that a supersymmetric description of D-term inflation is insufficient since the inflaton field reaches values of the order of at least the Planck mass, even if one concentrates around only the last 60 e-folds of inflation. Hence, the correct D-term inflation analysis should be within the SUGRA framework Rocher & Sakellariadou (2006). Moreover, D-term inflation must be described with a non-singular formulation of supergravity when the superpotential vanishes. To construct a formulation of SUGRA with constant FI terms from superconformal theory, one finds Binetruy *et al.* (2004) that under U(1) gauge transformations in the directions in which there are constant FI terms  $\xi_\alpha$ , the superpotential  $W$  must transform as  $\delta_\alpha W = \eta_{\alpha i} \partial^i W = -i(g\xi_\alpha/M_{\text{Pl}}^2)W$ ; one cannot keep any longer the same charge assignments as in standard supergravity. D-term inflationary models can be built with different choices of the Kähler geometry Rocher & Sakellariadou (2006).

Since cosmic strings Sakellariadou (2007) formed within a large class of high energy physics models (SUSY, SUGRA and string theories), one should consider mixed cosmological perturbation models where the dominant rôle is played by the inflaton field and cosmic strings have a small, but not negligible, contribution Bouchet *et al.* (2002). Restricting ourselves to the angular power spectrum we remain in the linear regime, where Bouchet *et al.* (2002),

$$C_\ell = \alpha C_\ell^{\text{I}} + (1 - \alpha) C_\ell^{\text{S}} ; \quad (6)$$

$C_\ell^{\text{I}}$  and  $C_\ell^{\text{S}}$  denote the (COBE normalised) Legendre coefficients due to adiabatic inflaton fluctuations and those stemming from the cosmic strings network, respectively and the coefficient  $\alpha$  is a free parameter giving the relative amplitude for the two contributions. Comparing the  $C_\ell$ , given by Eq. (6), with data obtained from the CMB measurements, one imposes constraints on the string tension Bouchet *et al.* (2002); Bevis *et al.* (2008); Urrestilla *et al.* (2011). The most recent Planck collaboration data impose severe constraints on the string contribution. More precisely, denoting by  $f_{10}$  the fraction of the spectrum contributed by cosmic strings at a multipole of  $\ell = 10$ , the Planck data imply Ade *et al.* (2013), for the Nambu-Goto string model that

$$f_{10} < 0.015 \text{ leading to } G\mu/c^2 < 1.5 \times 10^{-7} , \quad (7)$$

with  $G$  the Newton's constant and  $\mu$  the string tension.

The corresponding constraints for the Abelian-Higgs field theory model read Ade *et al.* (2013),

$$f_{10} < 0.028 \text{ leading to } G\mu/c^2 < 3.2 \times 10^{-7}. \quad (8)$$

### 3. Brane inflation

Within IIB string theory there are two classes of brane inflation models: D3/D7 inflation Dasgupta *et al.* (2002, 2004) and brane-antibrane inflation with D3/ $\overline{\text{D3}}$  Kachru *et al.* (2003) being the most studied example. The former is a string realisation of D-term inflation, where the rôle of a FI term is played by a non-self-dual flux on the D7-brane. The two (D3 and D7) branes are attracted to each other due to the breaking of SUSY by the FI term; inflation takes place in an unwarped background. The latter is a string realisation of F-term inflation, which is in general plagued by the  $\eta$ -problem. The brane is attracted to the antibrane due to warping. D3/ $\overline{\text{D3}}$  inflation takes place in a warped throat, as for instance the Klebanov-Strassler (KS) geometry; the warping resolves the  $\eta$ -problem of the standard F-term inflation.

To accept the two classes of brane inflation models studied within IIB string theory, one must firstly examine their theoretical consistency. More precisely, SUGRA is a consistent theory, in the sense that there is a globally well-defined Ferrara-Zumino multiplet, provided (i) the FI terms are field-dependent and (ii) the moduli space is non-compact. Assuming the SUGRA constraints remain valid in the full string theory, we will examine the consistency of the two classes of brane inflation and deduce Gwyn *et al.* (2010) severe consequences for the dynamics of the inflationary mechanism in the D3/D7 case. Note that often in brane inflation, it is desirable to leave the brane positions unfixed while the volume of compactification is stabilised. To examine whether the available brane inflation models are consistent with the SUGRA constraints, one has to consider the details of compactification and moduli stabilisation. Only once we are convinced that the brane inflation models satisfy the SUGRA constraints, it makes sense, as a second step, to investigate the observational consequences of the models and test their observational consequences against current measurements.

In the D3/D7 brane inflation model, a D3 brane is parallel to a D7 brane in the four noncompact directions, with the other legs of the D7 wrapping K3. The presence of a non-self-dual flux on the D7 brane leads to SUSY breaking and the appearance of an attractive potential between the branes. The inflaton field is given by  $\phi = x^4 + ix^5$  where  $x^4$  and  $x^5$  are the directions perpendicular to both branes, along which they feel the attractive potential. Inflation ends in a waterfall regime, when the open string modes stretched between the branes become tachyonic. Even though the FI term, which is due to a non-self-dual flux on the D7 brane, is field-dependent Gwyn *et al.* (2010), the present version of D3/D7 brane inflation fails to satisfy the SUGRA constraints Komargodski & Seiberg (2010). A successful D3/D7 inflationary scenario requires stabilisation of the Kähler modulus at a large finite value above the SUSY breaking scale, thus rendering the FI term constant Gwyn *et al.* (2011). A possible way out is to assume that quantum corrections will render the FI term to be dependent on the brane separation, however this would render the inflationary mechanism problematic since both the bifurcation point and the Hubble constant during inflation depend on the FI term.

In the D3/ $\overline{\text{D3}}$  brane inflation model, the brane-antibrane system lives at a specific point of a Calabi-Yau (CY) manifold, and the net attractive force between the brane and antibrane results from supersymmetry breaking. Here the brane-antibrane separation plays the rôle of the inflaton. To accommodate a sufficient number of e-foldings, the first and second slow roll parameters  $\epsilon$  and  $\eta$  must be very small and since  $\eta$  cannot be much smaller than unity in a flat space, D3/ $\overline{\text{D3}}$  brane inflation is realised in a warped geometry; the corresponding model is referred to as KLMT Kachru *et al.* (2003). Since this inflationary model is a stringy realisation of F-term inflation, there is no FI term, hence the first SUGRA constraint is not applicable.

The KLT D3/ $\overline{\text{D3}}$  brane inflation model can be made consistent with the second SUGRA constraint, in the sense that the moduli space of the theory can be made non-compact, through a SUSY breaking mechanism which in this model can be set at a scale independent of the volume modulus. Hence, the volume modulus can be fixed below the SUSY breaking scale, something which cannot be achieved for D3/D7 brane inflation.

#### 4. Radiation of cosmic (super)strings

Cosmic superstrings Sakellariadou (2010) produced at the end of brane inflation, can emit gravitational, axionic (Ramond Ramond (RR) or Neveu-Schwarz Neveu-Schwarz (NS NS) particles, since cosmic superstrings are charged under the two-forms  $B_2$ ,  $C_2$  which are Hodge dual to axionic scalars in four dimensions), or dilatonic radiation. As we have already discussed, to render cosmic strings compatible with the CMB data, the string tension gets severely constrained. In contrast to their gauge theory analogues, cosmic superstrings have in general Planck-scale energies and hence their high tension leads to  $G\mu/c^2 \sim 1$  Witten (1985) rendering them inconsistent with the CMB data. One should thus conclude that string inflation models leading to the production of cosmic superstrings with such high tensions must be ruled out. Hence, the IIB string theory motivated inflationary models that could be further examined are those realised within a warped geometry, as for instance brane-antibrane inflation in a throat, or models with large extra dimensions, since only in these cases the cosmic superstring tension gets suppressed.

In what follows we will briefly summarise Gwyn *et al.* (2010) the allowed channels of cosmic superstring radiation in warped backgrounds given our previous discussion (i) on the consistency of brane inflationary models with respect to the SUGRA constraints and (ii) on the constraints on the cosmic superstring tension. Taking into account a consistent compactification, we will see that severe constraints are imposed on the allowed radiation emitted from cosmic superstrings. Let us note that for gauge cosmic strings, gravitational radiation Vachaspati & Vilenkin (1985); Sakellariadou (1990) is the main channel of energy loss, allowing a cosmic string network to reach a scaling solution.

Cosmic superstrings produced at the end of brane inflation can be of three types: F-strings (the fundamental strings of the theory), D-strings (one-dimensional Dirichlet branes), or  $(p, q)$  string bound states of  $p$  F-strings and  $q$  D-strings. Considering a  $(p, q)$  string in a KS throat, the gravitational power radiated per unit solid angle is proportional to the square of the tension  $T_{(p,q)} = \sqrt{T_D^2 + T_F^2}$ , with  $T_D$  and  $T_F$  denoting the tensions of the D-string and F-string, respectively Gwyn *et al.* (2010). Further, since  $(p, q)$  strings are charged under the  $B_2^{\text{NS}}$  and  $C_2^{\text{RR}}$  2-forms, they may emit massless RR or NS-NS particles; the former are referred to as axions since the RR 2-form  $C_2$  is Hodge dual in four dimensions to the pseudo-scalar axion.

Considering axion emission from D-strings, it was shown Firouzjahi (2008) that the axionic radiation is

$$P_{\text{RR}} = \frac{\Gamma_{\text{RR}} \mu_1^2}{\pi^2 g_s \beta M_{\text{P}}^2}, \quad (9)$$

while the gravitational one reads

$$P_g = \Gamma_g G \left( \frac{h^2 \mu_1}{g_s} \right)^2, \quad (10)$$

leading to the ratio

$$\frac{P_{\text{RR}}}{P_g} = \left( \frac{8\Gamma_{\text{RR}}}{\pi\Gamma_g} \right) \frac{g_s}{\beta h^4}, \quad (11)$$

where  $\Gamma_{\text{RR}}, \Gamma_g$  are numerical factors of the order  $\mathcal{O}(50)$ ,  $g_s$  stands for the string coupling,  $h$  denotes the warp factor and  $\beta$  parametrises the difference in normalisations between the Chern-Simons and the Einstein-Hilbert term in the presence of warping. Thus, in the limit where  $g_s \ll 1$  and warping is negligible, power loss by gravitational radiation dominates over axionic radiation. However, in a warped geometry, as in the case of a KS background, since  $h$  can be much smaller than unity, one may naively conclude that axionic radiation becomes the dominant one. We will return to this point later in our discussion.

Considering F-strings, the NS-NS particle emission reads

$$P_{\text{NS-NS}} = \frac{\Gamma_{\text{NS}} \mu_1^2 g_s}{\pi^2 \beta M_{\text{P}}^2}, \quad (12)$$

which implies that the ratio of the axionic to the gravitational radiation is

$$\frac{P_{\text{NS-NS}}}{P_g} = \left( \frac{8\Gamma_{\text{NS-NS}}}{\pi\Gamma_g} \right) \frac{g_s^3}{\beta h^4}. \quad (13)$$

Hence, the NS-NS particle emission is suppressed as compared to the RR particle radiation.

The next interesting question is whether particle radiation can be dominant over the gravitational one in the case of  $(p, q)$  strings. This is an important issue since it may highlight an observational difference between comic superstrings and their gauge analogues, at least in the case that the former are produced in a warped throat. Let us first remark that, as we have pointed out in Ref. Gwyn *et al.* (2010), the enhancement of RR particle emission claimed for D-strings in Ref. Firouzjahi (2008) is due to the effect of warping. However, as discussed in Ref. Gwyn *et al.* (2010), the allowed radiation channels are constrained from the orientifold projection imposed by a consistent flux compactification. The only known consistent compactification of the Klebanov-Strassler geometry is the flux compactification proposed by Giddings, Kachru and Polchinski (GKP) in Giddings *et al.* (2002), which involves an orientifold projection  $\mathcal{O}$  whose action on the NS-NS and RR two-forms reads

$$\mathcal{O}B_2 = -\sigma^* B_2 \quad \text{and} \quad \mathcal{O}C_2 = -\sigma^* C_2, \quad (14)$$

respectively, where  $\sigma^*$  is the pull-back of an isometric and holomorphic involution  $\sigma$ . Noting that the internal symmetry  $\sigma$  acts on the internal manifold while it leaves the four-dimensional non-compact space invariant, one concludes that the NS-NS and RR two-forms with legs in the non-compact directions are projected out Grana *et al.* (2004). This observation has important consequences for the allowed radiation channels. More precisely, since the zero modes of  $B_{\mu\nu}$  and  $C_{\mu\nu}$  do not appear in the spectrum Copeland *et al.* (2004), there can be no massless RR or NS-NS axions Gwyn *et al.* (2010). As it has been argued in Ref. Gwyn *et al.* (2010), neither D- nor F-strings can lead to significant axionic emission, since by construction of the brane inflationary model within which they are formed, D- and F-strings will not have any massless axionic radiation. However, for a  $(p, q)$  string arising from a wrapped D3-brane, the situation may be different. In this case, while NS-NS particle radiation is completely ruled out, RR radiation may be possible since  $(p, q)$  strings are also charged under the RR four-form  $C_4$ .

However, to determine the allowed modes of radiation by cosmic superstrings within a warped geometry, one should consider not only which modes will survive the orientifold projection, but one should also keep in mind the correct dimensional reduction of those modes. As it has been pointed out in Ref. Underwood (2011), the wave-function of the axionic zero mode is non-trivially modified by warping, however there is only limited progress in understanding this modification. Since the resulting wave-function would affect the magnitude of any radiation in this mode, lack of knowledge of the modified wave-function implies that we are not yet in a position to quantify the amplitude of the radiation.



Finally, cosmic superstrings may also emit dilatonic radiation. As is well-known, massive dilatons are compatible with astrophysical observations only if they acquire a Vacuum Expectation Value (VEV) before nucleosynthesis. Indeed, the dilaton gets a non-trivial potential in the GKP compactification, however the mass of the dilaton located in the throat will be suppressed by the warp factor.

In a warped geometry, the constraints Babichev & Kachelriess (2005) on cosmic superstring tension as a function of the dilaton mass are weakened Sabancilar (2010) since the mass gets suppressed by the warp factor and the dilaton wave-function is localised in the throat with an exponential fall off in the bulk, resulting to an enhancement of the dilaton to matter coupling.

## 5. Concluding remarks

Cosmic (super)strings seem to be generically formed at the end of an inflationary era in the context of inflationary models built within supersymmetric grand unified theories, supergravity, or even string theory models. These objects decay emitting gravitational waves and particles, the gravitational radiation being, most probably, the dominant decay channel.

As a contradiction to our theoretical expectations and despite various efforts we have not yet identified any such objects in the sky, while temperature anisotropies data constrain severely their potential cosmological rôle in structure formation. As a result, the allowed string tension decreases constantly rendering cosmic (super)strings weaker and therefore diminishing any gravitational implications they may have. However, since the inflationary scale is related to the string tension, one cannot freely constrain the tension of the strings without questioning the implications for the inflationary model within which strings were formed.

Conventional and well-studied inflationary models face some questions, with the onset of inflation and the origin of the inflaton field being the most important ones. To this list we have added one more, namely the compatibility between the constraints on string tension and the validity of the currently well-studied inflationary models. Absence of topological defects may imply lack of knowledge of the thermal history of the universe, which will certainly affect our understanding of inflation.

Let us end by stressing that our conclusion is not to rule out inflation but to emphasise that a number of the currently available models may turn out to be unphysical or inconsistent with the theoretical framework upon which they were based.

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